Feedback of anti-G straining performance of pilots: The use of the ear pulse waveform as a feedback signal for blood pressure

Author(s)
M. Holewijn, M. van de Endt, J. Rijkelijkhuizen, M. Los

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Executive Summary

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Title : Feedback of anti-G straining performance of pilots; the use of the ear pulse signal as a feedback signal for blood pressure
Authors : M. Holewijn, M. v. d. Endt, J. Rijkelijkhuizen, M.Los
Institute : Aeromedical Institute, Soesterberg, The Netherlands

As a part of a joint study of the National Aeromedical Institute (Soesterberg, the Netherlands), the National Aerospace Laboratory (Amsterdam, the Netherlands) and the Polish Air Force Institute of Aviation Medicine (Warsaw, Poland) an in-flight experiment was performed to evaluate the use of psycho-physiological measures as feedback parameters of physiological and mental strain. In a previous report, feedback parameters that could improve pilot flying performance were reported (Hanson 1998). The main goal of this report was to evaluate the use of the ear pulse arterial waveform as a potential feedback parameter of the blood pressure status during accelerations. This project was carried out under a contract of the Dutch Ministry of Defense.

Pilots in high performance aircrafts are frequently exposed to high G_z-forces, causing a redistribution of blood to the lower extremities. As a result, blood pressure at head level decreases and a pilot can lose consciousness. The pilot can partly counteract the drop in blood pressure by performing an anti-G straining maneuver. However, if the exposure to high acceleration is sustained, loss of consciousness may occur. Until now, no operational system is available to monitor in-flight the pilot's physiological state during high acceleration maneuvering. On basis of the measurement of ear pulse arterial waveforms, the Aeromedical Institute has recently developed a simple hardware prototype and the analysis algorithms to monitor blood pressure changes at head level. In order to test this prototype system as an on-line feedback system, in-flight measurements were performed during aerobatic maneuvers.

The results of this study showed that the amplitude of the ear pulse waveform decreases with increasing acceleration during aerobatic profiles. The pulse transit time (PTT) of the ear pulse waveform increases with increasing acceleration during aerobatic profiles. These changes are in agreement with the hypothesis that they reflect a decrease in blood pressure at head level during acceleration. Heart rates did not show a correlation with the acceleration levels during the investigated aerobatic profiles. Possibly, this is because the response time of heart rate regulations, being not fast enough to follow the changes of the accelerations in the aerobatic profiles.

The results of this study support the use of the amplitude and the PTT of the ear pulse waveform as an online feedback parameter of changes in blood pressure at head level, during exposure of a pilot to accelerations.

Contents

1 Introduction

Pilots in high performance aircrafts are frequently exposed to high G_z-forces, causing a redistribution of blood to the lower extremities. As a result, blood pressure at head level decreases (Agard, 1995; Burns, 1992; Burton, 1991). If the pilot is subjected to high and/or sustained G_z-forces, loss of peripheral vision will occur. This is called peripheral light loss (PLL) (Agard, 1990). Higher and/or longer exposures may result in a totally reduced visual field (black-out) and finally the pilot can experience a G-induced loss of consciousness (G-LOC) (McCloskey et al., 1992; Wood, 1987). The pilot can counteract the drop in blood pressure by performing an anti-G straining maneuver and by wearing anti-G garment. However, if the onset rate of the acceleration is too fast or the anti-G straining maneuver is performed inadequately, blood pressure may drop critically, resulting in a G-LOC. Until now, no operational system is available to monitor the pilot's blood pressure state during high acceleration in-flight maneuvering.

Furthermore , (candidate) military pilots are trained in a human centrifuge to optimize the anti-G straining maneuver. During this centrifuge training the trainee is monitored by means of ECG and a video system. No objective information is available to the trainee or supervisor about the actual blood pressure or about the effectivity of the performance of the trainee's anti-G straining manoeuver. During the onset of the G_z-acceleration less muscle tension is necessary than during high G_z-forces (Gillingham, 1987). The trainee is learned to improve his anti-G straining maneuver only on basis of verbal feedback of the supervisor. The supervisor gives his feedback mainly based on the trainee's timing of his in- and exhalation, and not on an objective parameter for blood pressure at head level.

Until now, a limited number of prototype systems were developed to monitor head level blood pressure in a centrifuge (Cammarota, 1991; Holewijn e.a. 1994; Hrebien, 1988; Jaron et al., 1987; Wood, 1990; Wood and Sturm, 1989), but with limited practical results. These biofeedback systems were based on the oxidative status of the brain (Glaister, 1988), velocity of blood flow (Chiu et al., 1991), blood pressure on head level (LaCourse et al., 1991; Glaister, 1988) and the arterial ear pulsations (Hebrien 1988; Jaron et al. 1987; Wood, 1987; Wood, 1990). However, none of these systems were generally accepted as a feedback system in a centrifuge due to several (practical) factors. To be applicable in more than experimental studies the system must be reliable, non-invasive, small (so that it can be worn under a pilot helmet) and it must sustain high loads that occur during flight (Whinnery, 1989).

At the National Aeromedical Institute several experiments were dedicated to develop a demonstrator for a blood pressure feedback system. This system is based on the arterial ear pulsations, a so-called ear pulse waveform monitor. This system is a photo electrical transilluminal plethysmograph measuring the blood volume pulsations in the vascular bed of the ear pinna by means of measuring the amount of infrared light absorbed by the ear pinna. There are several advantages in the use of the ear pulse waveform as an indicator of the onset of blood pressure changes (Holewijn e.a. 1994; Wood, 1990). The most important advantages of a system based on the ear pulse waveform is that it

provides information on circulatory parameters at head level. Other advantages are that the ear pulse waveform is relatively insensitive to psychological and physiological strain (Challoner, 1979; Dorlas and Nijboer J.A, 1985; Hertzman, Dillon, 1939; Nijboer, Dorlas and Mahieu, 1981; Stern, 1974) and the fact that the sensor is electronically simple, small and relatively cheap.

The amplitude of the ear pulse waveform changes in phase with variations in blood volume pulsations due to each heart beat (Nijboer, Dorlas and Mahieu, 1981). In an in vitro experimental study D'Agrosa and Hertzman (1967) and Chaloner (1979) detected changes in amplitude of the ear pulse waveform, without changes in the diameter or blood volume of isolated arteries. These authors proposed that the amplitude of the plethysmogram changed as the result of changes in the orientation of erythrocytes, affecting the reflection of (infra)red light, and not as the result of blood volume pulses. However, Nijboer, Dorlas and Mahieu (1981) showed clearly that under normal (in vivo) situations this effect of reflection by the erythrocytes is far dominated by their absorption capacity for (infra) red light. As the total amount of absorption is dependent on the amount of erythrocytes, blood volume variations will be detected as variations in the amount of absorbed (infra)red light. Thus, it can be assumed that the amplitude of the ear pulse waveform will be proportional to the blood volume pulses in the ear pinna.
Besides the amplitude of the ear pulse waveform another parameter, the pulse transition time (PTT), can be derived. PTT is defined as the time shift between the start of the ejection of the blood during each cardiac cycle and the arrival of the pressure pulse at a peripheral measuring point. It has been shown in other studies that PTT is related to blood pressure (Callaghan et al, 1986; Gedes et.al 1981; Gribbin et al, 1976). Hrebien (1988) showed that the PTT of an arterial pulse wave is inversely related to blood pressure. Steptoe et al. (1976) found high linear correlations (r=0.91 - 0.98) between PTT and arterial pressure.

As a part of a joint study of the National Aeromedical Institute (Soesterberg, the Netherlands), the National Aerospace Laboratory (Amsterdam, the Netherlands) and the Polish Air Force Institute of Aviation Medicine (Warsaw, Poland) an in-flight experiment was performed to evaluate the use of psycho-physiological measures as feedback parameters of physiological and mental strain. In a previous report feedback parameters that could improve pilot performance were reported (Hanson 1998). In the present report the effects of physiological strain due to exposure to vertical accelerations (G_z strain) on the blood pressure at head level will be reported. The main goal of this study was to evaluate the use of the ear pulse arterial waveform as a potential feedback parameter of a pilot's blood pressure status during accelerations. This project was carried out under a contract of the Dutch Ministry of Defense.

2 Methods and Materials

2.1 Subjects

Eight young male student civil pilots participated in a study on the development of feedback parameters of a pilot's training performance. All the subjects had a current private pilot's license. The main objective was to collect flight information to enable the creation of a pilot debriefing facility of relevant flight parameters (Hanson 1998). Beside the collection of The subjects did not had prior anti-G-straining experience. The pilots had a mean age of twenty-four years (range 22-26 years), mean weight of 73 kg (range 67-82 kg) and a mean length of 1.88 m (range 1.84-1.95 m). Each pilot entered an aerobatics-training program (ten lessons) in a 180 hp Decathlon Bellanca aerobatics aircraft of a flying school, situated at Lelystad Airport, the Netherlands.

2.2 Physiological measurements

The physiological measurements were done during the seventh lesson. As physiological parameters respiration, ECG and the ear pulse signal were measured. They were recorded on a VITA-PORT-II data logger at different sampling rates. All signals were fed through a separate channel, pre-processed and stored on a 350-Mb RAM card. The ECG and the ear pulse were sampled at 256 Hz; the respiration and vertical acceleration were sampled at 16 Hz. The respiration data will not be analyzed in this report. Due to technical problems a complete data set of physiological measures of four pilots was obtained. The most frequent causes of data loss were loose ECG electrodes (2 #) causing noise on the signal or a failed G_z registration (2#).

Ear pulse waveform

The continuous ear pulse waveform was measured with a custom-built transilluminal photoplethysmograph, consisting of a Telefunken Silicon Photo PIN diode (BPW34) and a Silicon Planar PN Photovoltaic Cell (BPW35). A Fleishman 9808 lightbulb was used as light source and filtered with a filter of 900 nm (near infrared). The signal was bandpass filtered (0.1-25 Hz) with a 3dB/oct hardware filter before A/D conversion on disk. The ear pulse waveform was off-line processed in a data processing software package (Windaq 1.68, Dataq Instruments Inc). The ear pulse waveform was bandpass filtered between 0.6 and 12 Hz by means of Fourier inverse filtering. From the ear pulse waveform the amplitude and the pulse transit time of each pulse were determined (Fig. 1). The onset of each ear pulse waveform was determined by means of peak detection on the second derivative of the ear pulse waveform signal. This point in the waveform was defined as the valley of an ear pulse waveform. The peak value of an ear pulse waveform was defined as the maximal value of the pulse. The amplitude of the ear pulse waveform was calculated as the difference between the peak and the valley (Fig. 1). As the ear pulse waveform is not a calibrated signal, all ear pulse amplitude data are presented as relative values compared with a reference value. The mean value of the amplitudes of the ear pulse waveform of each subject, recorded during the last

fifty seconds of the first baseline in-flight period (5 min) preceding all aerobatics maneuvers, was used as a reference value.

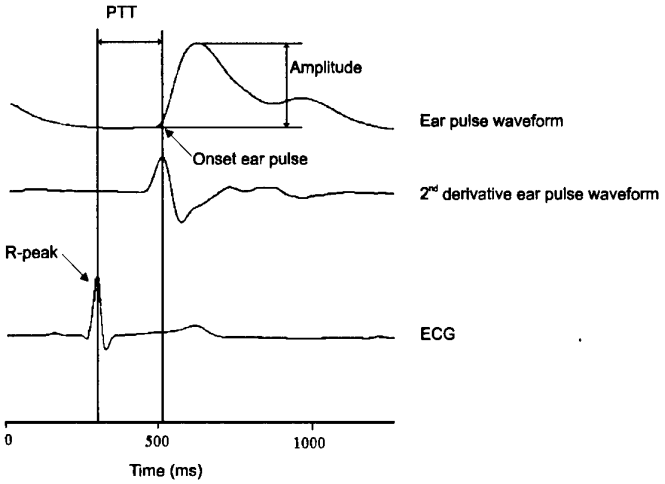

Fig. 1. The calculated amplitude and the pulse transit time (PTT) derived from the ear pulse waveform.

The pulse transit time (PTT, ms) of an ear pulse waveform was defined as the time between the R-peak of the ECG and the onset of the ear pulse waveform. Similar to the transformation of the amplitude, all the calculated PTT values were transformed to relative units compared with the mean PTT reference value of the last fifty seconds of the first baseline in-flight period (5 min) preceding all aerobatics maneuvers.

ECG

The R-peaks were derived from the ECG signal using a custom built hardware R-top detection trigger. After skin preparation with alcohol, two active electrodes (ARBO type N66 Ag/AgCl foam) were placed 4 cm above the jugular notch of the sternum and on the apex of the heart over the ninth rib, and the ground electrode was placed above the right iliac crest. The ECG signal was bandpass filtered at 1-100 Hz in the VITAPORT-II before A/D conversion.

G_z-strain

Linear accelerations in three dimensions were measured with an analogue STAS hardware. Two pressure transducers (Rosemount, PS&PT) were used to measure static and total pressure, from which altitude, speed and acceleration were be derived.

2.3 Experimental procedure

After briefing the pilot, the sensors were applied and the student pilot, wit the instructor, took their seats in the aircraft. In-flight the instructor asked the pilot to perform three aerobatics maneuvers: a loop, a split-S (Fig. 2) and a sequence of a loop, a slow roll, an inverted flight, an Immelman- maneuver and a split-S.

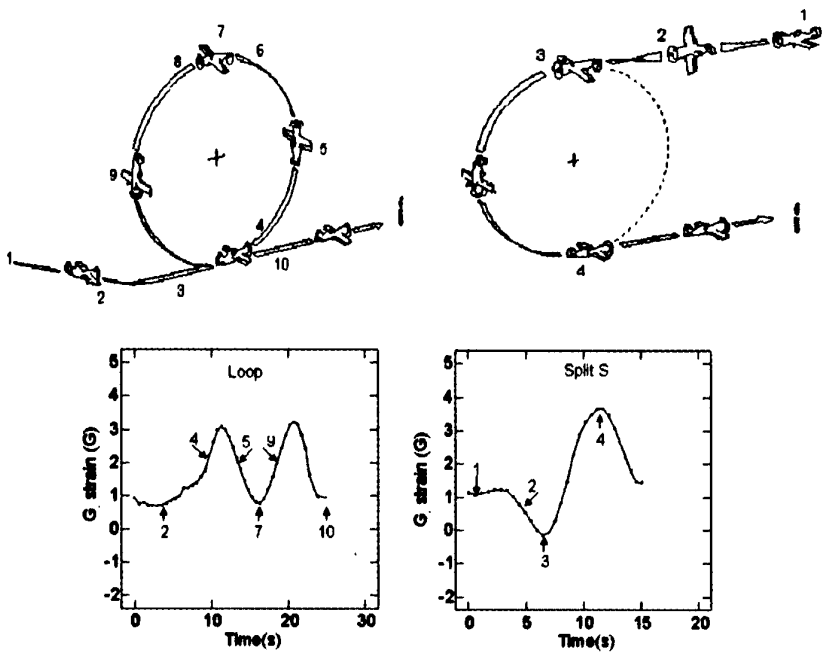

Fig. 2. The two aerobatic profiles used in this study. In the upper panel a graphical display is given of the Loop (left) and the Split-S (right) profile and in the lower panel the amount of vertical acceleration (G_z strain) at the corresponding points in the profile.

It can be seen in Fig. 2 that the Split-S profile, compared with the Loop profile, is shorter in time, but consisted of a longer period of increasing G_z strain due to the fact that the G_z strain first drops to below zero G and than increases to a G_z strain of 3 G. In this report only the data of the Loop and the Split-S profile will be discussed and not the data of the sequence of consecutive profiles. A 5-minute baseline period preceded and followed all the aerobatics maneuvers. During the baseline period subjects were asked to fly straight level.

2.4 Statistics

Data per subject will be shown to enable the discussion of the individual reactions. Data will be shown for the whole profile and for those periods of the profile in which the G_z strain was increasing. This was done as was expected that due to the continuously changing G_z strain levels the physiological adaptations would be time-lagging in reactions to a decreasing G_z strain after a period of increasing G_z strain.
Nonlinear quadratic and linear regression analyses were done between the different physiological variables and the G_z strain with the statistical software package Systat (version 7.01, SPSS inc).

3 Results

In Fig. 3 a typical recording of subject four is given, showing the changes in the heart rate, and the amplitude and the PTT of the ear pulse waveform during the 'loop' profile. The effects of the G_z strain can be clearly seen on the amplitude and the PTT of the ear pulse waveform. Less effect of the G_z strain level is visible in this subject on the heart rate.

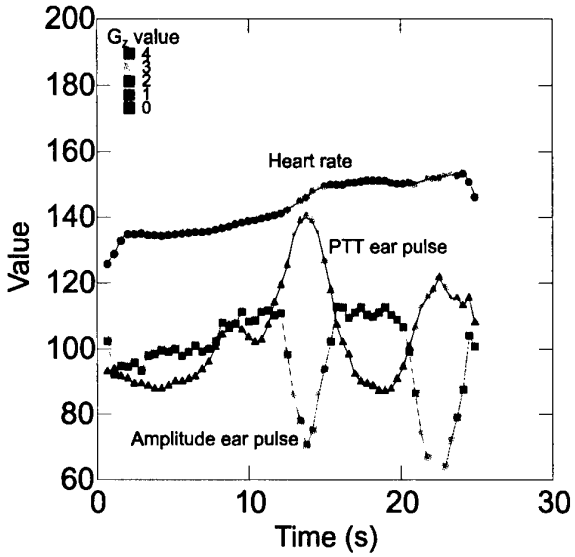

Fig. 3. Typical changes of the heart rate (beats/min) and of the amplitude (% reference period) and PTT (% reference period) of ear pulse waveform during the Loop profile. The G_z level during the profile is indicated with the color of the individual datapoints.

In general it can be seen that during increasing G_z strain the amplitude of the ear pulse waveform decreases, whereas the PTT of the ear pulse waveform is increasing. In the following sections the effect of the G_z strain on the different physiological measures will be discussed in detail.

3.1 Amplitude of the ear pulse waveform

During the Loop profile two subjects (two and four) showed a decrease of the amplitude of the ear pulse waveform with increasing G_z strain (Fig. 4). One subject (n° 1) showed a slight decrease, but subject n° 3 showed a marked increase with increasing G_z strain. No change was found in the relationship between amplitude of the ear pulse waveform and the G_z strain if the periods with increasing G_z strain in the Loop profile were selected. It is also visible in Fig. 4 (lower panel) that most of the subjects exhibited a small shift in the data points, as the result from the Loop profile consisting of two consecutive peaks in the G_z strain (Fig. 2).

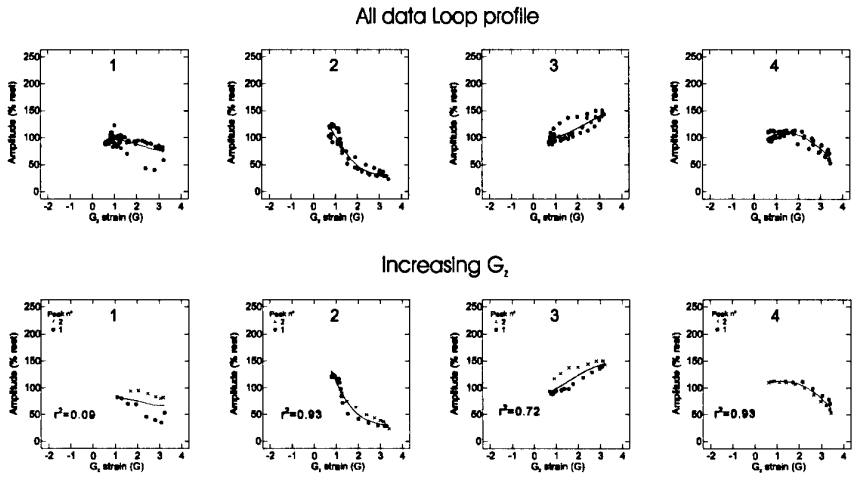

Fig. 4. The relation between the amplitude (% rest value) of the ear pulse waveform of the four subjects and the G_z level during the Loop profile. All data of the four subjects are shown in the upper figures, and in the lower four figures only the data are shown for periods in the profile with increasing G_z values. Also in the lower panel the data for the first G_z peak (•) and for the second G_z peak (x) in the Loop profile are indicated.

In the Split-S a similar relationship was found between the amplitude of the ear pulse waveform and G_z strain (Fig. 5).
It should be noted that during this profile the pilot is subjected to a period of a G_z strain that is less than 1G and even negative (Fig. 2). All subjects showed a

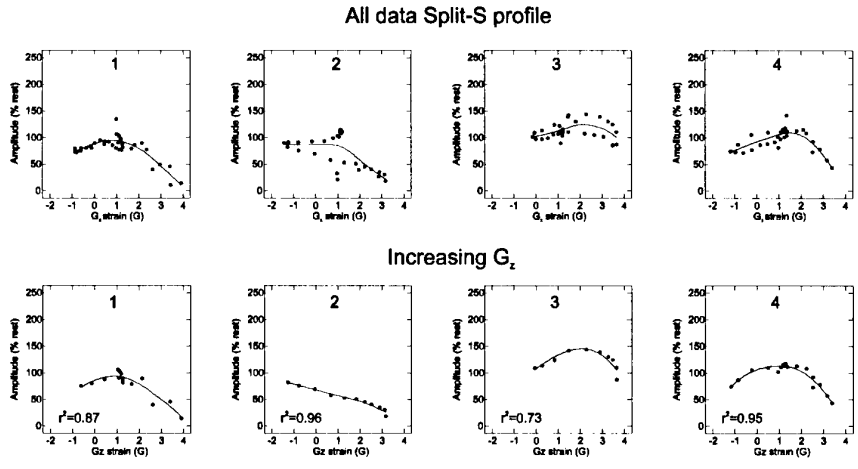

Fig. 5. The relation between the amplitude (% rest value) of the ear pulse waveform of the four subjects and the G_z level during the Split-S profile. All data of the four subjects are shown in the upper figures, and in the lower four figures only the data are shown for periods in the profile with increasing G_z values.

tendency to decrease the amplitude of the ear pulse waveform if the G_z strain was above 2 G. Less scatter was found in the relationship between amplitude of

the ear pulse waveform and the G_z strain if only the periods with increasing G_z strain in the Loop profile were selected (Fig 5, lower panel).

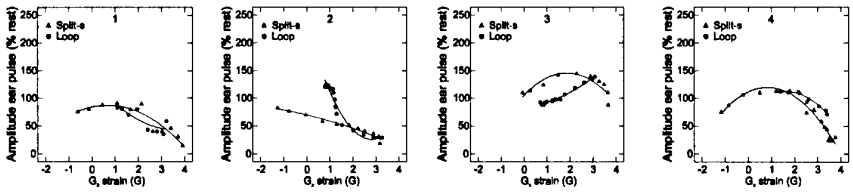

Fig. 6. The relation between the amplitude (% rest value) of the ear pulse waveform of the four subjects and the G_z level during the Loop (●) and Split-S (▲) profile.

When the relation between the amplitude and the G_z strain for the Loop and the Split-S profile are compared, it can be seen that for subjects 1 and 4, the effect of G_z strain on the amplitude of the ear pulse waveform was similar (Fig. 6). For subjects 2 and 3, the effect of G_z strain on the amplitude of the ear pulse waveform showed differences for both profiles, in particular in the region of low G_z strain.

3.2 Pulse transit time (PTT) of the ear pulse waveform

In Fig. 7 the effects of the G_z strain on the PTT during the Loop profile are shown. All four subjects showed a curvi-linear relationship between the G_z strain and the PTT of the ear pulse waveform. Increasing G_z strain resulted in an increase of the PTT.

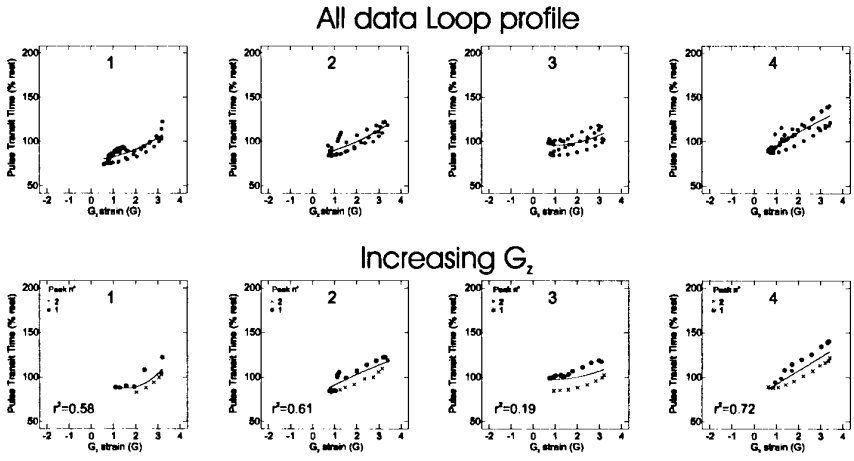

Fig. 7. The relation between the PTT (% rest value) of the ear pulse waveform of the four subjects and the G_z level during the Loop profile. All data of the four subjects are shown in the upper figures, and in the lower four figures only the data are shown for periods in the profile with increasing G_z values. Also in the lower panel the data of the first G_z peak (•) and of the second G_z peak (x) in the Loop profile are indicated.

As was visible in the amplitude response, a 'history effect' of the G_z strain was found on the PTT response. The PTT changes were dependent of the G_z strain

peak in the Loop profile. The data measured during the second G_z strain peak (x) were lower than the data of the first peak(•) (Fig. 7, lower panel).

During the Split-S profile a similar response of the PTT of the ear pulse waveform due to changes in the G_z strain was found in all subjects (Fig. 8). The PTT of the ear pulse waveform increased curvi-linear with increasing G_z strain. Also, less scatter is found when only the period of increasing G_z strain was selected (Fig. 8, lower panel).

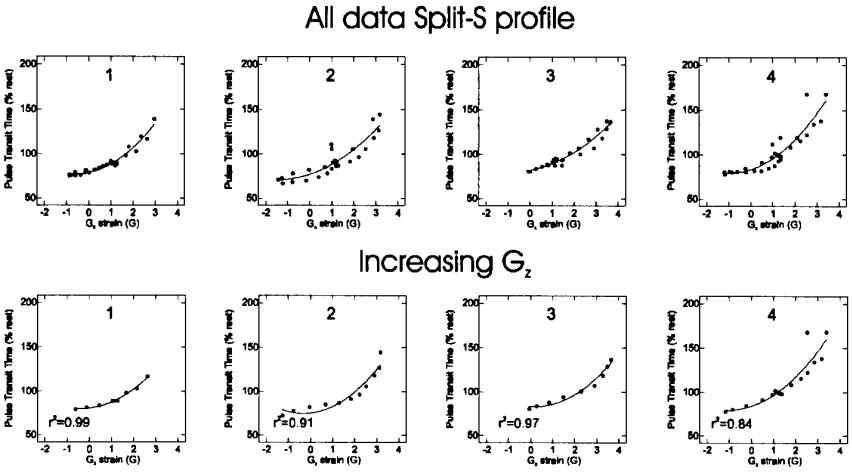

Fig. 8. The relation between the PTT (% rest value) of the ear pulse waveform of the four subjects and the G_z level during the Split-S profile. All data of the four subjects are shown in the upper figures, and in the lower four figures only the data are shown for the period in the profile with increasing G_z values.

The effects of G_z strain on the PTT of the ear pulse waveform during both profiles are similar (Fig. 9).
There is a gradual increase of the PTT of the ear pulse waveform from negative G_z levels up to positive G_z levels. The PTT of the ear pulse waveform is at a level of -1 G_z around 75% of the PTT value at 1 G (reference condition), and increases up to 150% at 3-4 G.

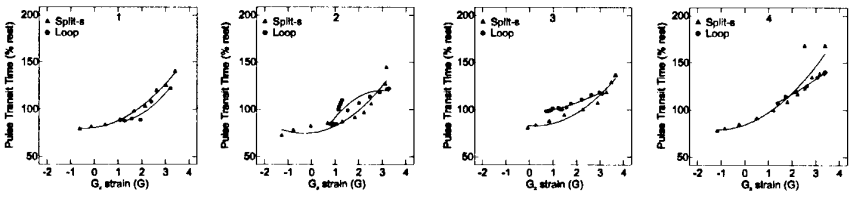

Fig. 9. The relation between the PTT (% rest value) of the ear pulse waveform of the four subjects and the G_z level during the Loop (•) and the Split-S (▲)profile.

3.3 Heart rate

As was expected an increased G_z strain resulted in a higher heart rate (Fig. 10). However, the relationship between the heart rate and the G_z strain was ambiguous and exhibited hysteresis for all four subjects and for both profiles. This resulted in a scatter in the heart rate of 10-20 beats/min at a G_z level. As can be seen there was considerable inter-individual variation in the heart rate response, and the between aerobatics profile variations were small.

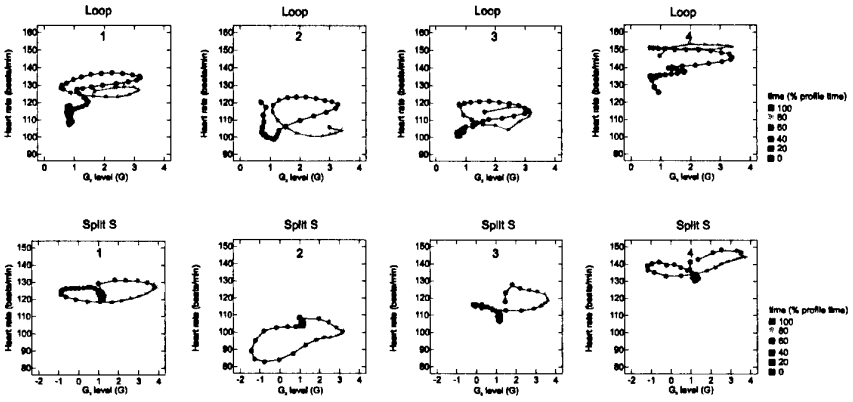

Fig. 10. The effect of G_z level during the Loop (upper figures) and the Split-S (lower figures) profile on the heart rate (beats/min). Also the time is indicated with the color of the data points.

In order to extract the heart rate adaptations more clearly for the periods of increasing G_z levels, only the heart rates for these periods are shown in Fig. 11.

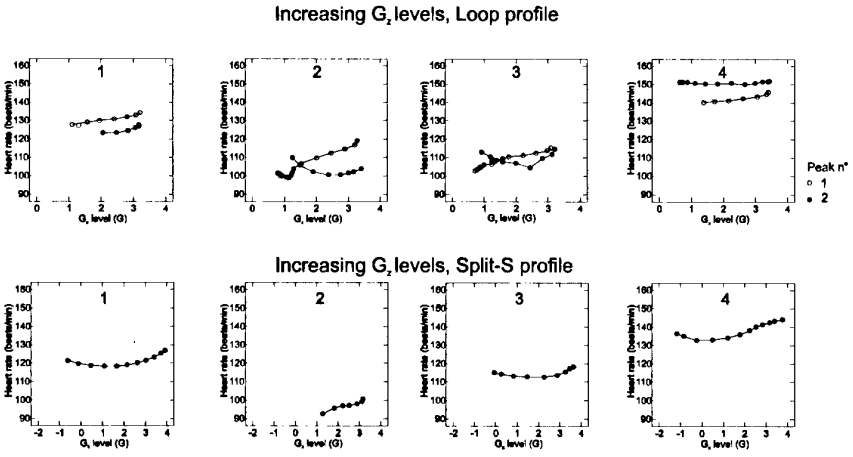

Fig. 11. The effect of G_z level during the Loop (upper figures) and the Split-S (lower figures) profile on the heart rate (beats/min) for periods of increasing G_z. For the Loop profiles, the datapoints for the first peak (○) and for the second peak(●) are separately indicated and connected in time sequence.

It can be seen that even for the duration of the selected period of increasing G_z, the level of G_z strain does not unequivocally affected the heart rate. In addition,

the adaptations of the heart rate were different for the two consecutive G_z peaks during the Loop profile,.

3.4 Relation between ear pulse waveform parameters and heart rate

To investigate the relationship between the ear pulse waveform parameters and the heart rate, the heart rate and ear pulse data of profile period with increasing G_z strain were selected (Fig. 12).
During the Loop and the Split-S profile a high heart rate is associated with a low amplitude and a high PTT of the ear pulse waveform. Only subject n° 3 showed an increase in the amplitude of the ear pulse waveform in combination with an increase of the heart rate during the Loop profile (Fig. 12). It should be noted that there is considerable variation between the four subjects and the two aerobatics profiles.

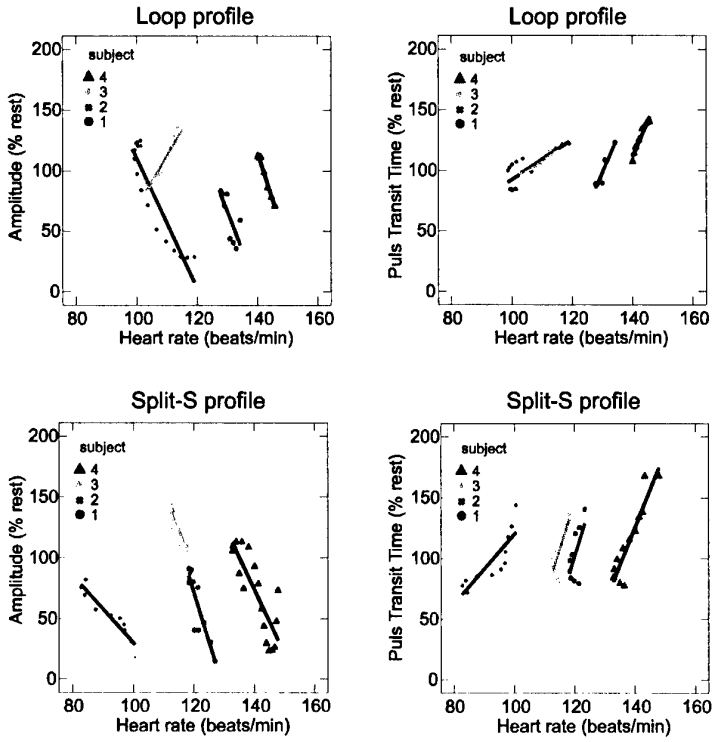

Fig. 12. The relation between the heart rate(beats/min) and the amplitude (%, rest value) and the PTT (%, rest value) during the upward slope of the first G_z peak in the Loop (upper panel) and the Split_s (lower panel) profile for four subjects.

Between the amplitude of the ear pulse waveform and the heart rate a linear regression line per subject and per profile could be fitted, with a squared correlation coefficient varying between 0.64 and 0.94. Between the PTT of the ear pulse waveform and the heart rate a linear regression line per subject per profile could be fitted with a squared correlation coefficient varying between 0.55 and 0.98.

However, if all heart rate and the ear pulse waveform data of the entire Loop and the Split-S aerobatic profiles were used no relationship is visible (Fig. 13).
A non-linear quadratic regression line could be fitted per subject between the PTT of the ear pulse waveform and the heart rate data of the two aerobatic profiles with a squared correlation coefficient varying between 0.05 and 0.19.

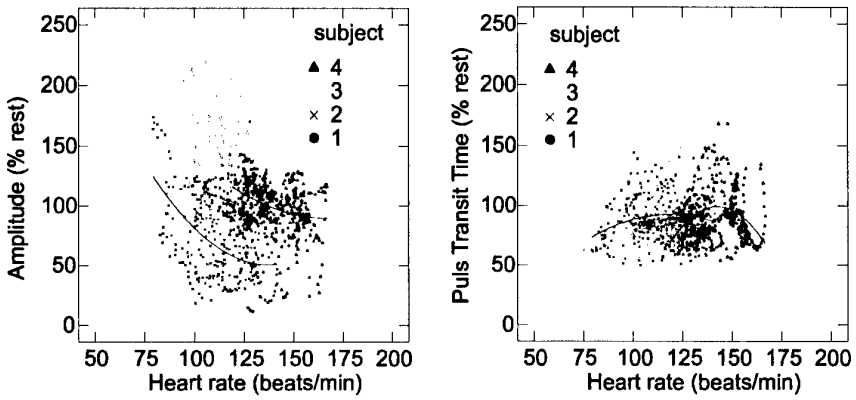

Fig. 13. The relation between all the heart rate(beats/min) and the amplitude (%, rest value) and the PTT (%, rest value) during the entire period of the Loop and the Split-S profiles.

4 Discussion

The main goal of this study was to evaluate the in-flight application of the ear pulse waveform as an indicator of individual blood pressure changes as a result of vertical (G_z) accelerations.
The results of this in-flight study indicate that during aerobatic maneuvers the amplitude and the PTT of the ear pulse waveform were influenced by the G_z-level. In the region of higher G_z ($> 3G_z$) the subjects showed a decrease in the amplitude in combination with an increase of the PTT. In the region of lower G_z levels ($<3G_z$) the relationship showed differences between the two aerobatics profiles. The absolute G_z-level at which the changes in the ear pulse waveform parameters started and the rate of change was subject dependent. The data from this study suggest that the PTT had a higher reproducibility and correlation with the G_z-strain during the two different profiles than the amplitude of the ear pulse waveform.

A decrease of the amplitude and an increase of the PTT of the ear pulse waveform with increasing G_z-strain is in accordance with other studies (Holewijn et al., 1994; Hrebien , 1988; Jaron et al. 1987; Wood and Sturm, 1989). These studies showed that the amplitude of the ear pulse waveform decreased to zero (no pulsations) a few seconds before the moment of peripheral light loss (PLL). This decrease of the amplitude of the ear pulse waveform is the result of a drop of blood pressure at head level. A drop of blood pressure to critical low levels for for several seconds will diminish the perfusion of the brain, causing a loss of consciousness. (Holewijn et al., 1994; Hrebien,1988; Jaron et al. 1987; Wood and Sturm, 1989).
The G_z level at the moment of PLL is often used as the (maximum) level of a

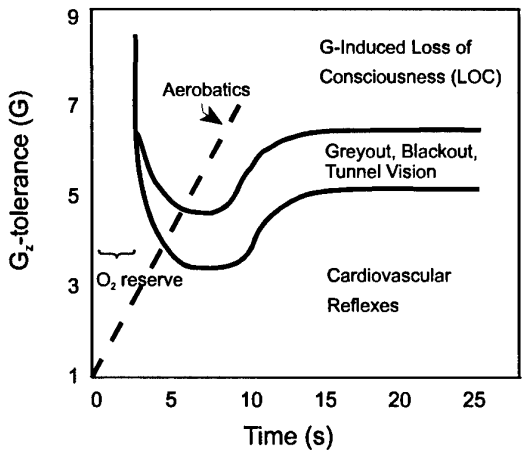

Fig. 14. Tolerance to Gz acceleration dependent on the onset rate and duration of exposure (modified figure from Glaister, 1988). Typical onset rate for aerobatic profiles is depicted by the dotted line.

subjects G_z tolerance. A decrease of the amplitude of the ear pulse waveform to zero was not found in this in-flight study. It is therefore assumed that the

subjects did not reach their G-tolerance level. According to Glaister (1988) G_z accelerations up to 9 G can be tolerated for a few seconds due to the oxygen reserve in the brain (Fig. 14).
When the exposure is limited to 10 s, the onset rates have to be lower (<0.5 $G \cdot s^{-1}$) and the G_z levels are restricted to 3-4 G, so that cardiovascular reflexes can be effective. These cardiovascular reflexes are capable to maintain cerebral blood pressure at adequate levels. Longer exposures to acceleration can be tolerated, however the onset rates have to be lower (Fig. 14). When a combination of G-level and exposure time falls within the two curved lines, a pilot will experience visual symptoms, like gray -out, blackout, and tunnel vision (Fig. 14). When a combination of G-level and exposure time falls above the upper curved line a pilot will experience a Loss of Consciousness due to G (G-LOC). In Fig. 14 it can be seen that if typical aerobatics onset rates are plotted, aerobatic maneuvers of 3-4 G have to be sustained for more than 5s in order to reach the G-tolerance of a pilot. These periods of exposure to these G_z-levels are not found in the two profiles and therefore no amplitude reductions to zero will be be found, which is in agreement with the results. This is also substantiated by the fact that no pilot reported a PLL during the two profiles.

It it hypothesized that the increase in the PTT of the ear pulse waveform with increasing G_z-strain during the aerobatics profiles (Fig. 7 and 8) is due to decreasing blood pressure. It is well known that PTT is dependent on the changes of the elasticity of the blood vessel, as the result from variation in the blood pressure. This effect of pressure on pulse propagation was already described in 1878 by Moens and Korteweg. The relation between the PTT and the arterial wall's Young's modulus of elasticity (E) can be described by the Moens and Korteweg equation as:

$$PTT = L/\sqrt{(E*t/\rho*d)}$$

with
L= length of a blood vessel
E= Young elasticity modulus
t= vessel wall thickness
ρ= blood density
d= vessel lumen diameter

When blood pressure increases, the wall thickness (t) decreases and the diameter of the blood vessel increases. This should result in an increase of the PTT, but it is overshadowed by the opposite effect of the blood vessels elasticity changes on the PTT. The elastic modulus (E) of an artery increases exponentially with increasing blood pressure, according to

$E = E_o^{\alpha P}$
E_o= zero pressure modulus
α=coefficient dependent on the vessel type (for arteries fflo.0017)
P=blood pressure in mmHg

In total, the PTT will decrease with increasing blood pressure overshadowing the effects of a decrease in vessel thickness and increase in a vessel diameter (Pruett et al., 1988).
Results from experimental studies are in agreement with the theory described above, showing that PTT increases with a drop in mean blood pressure. Both Sinn (1956) and Pruett et al. (1988) reported a significant increase of the PTT with decreasing mean blood pressure (Fig. 15).
It is therefore concluded that the increase in the PTT found during the aerobatics profiles represent a drop of blood pressure on head level. However it remains unclear to what absolute level the blood pressure dropped, as in this in-flight study no blood pressure measurements were performed due to

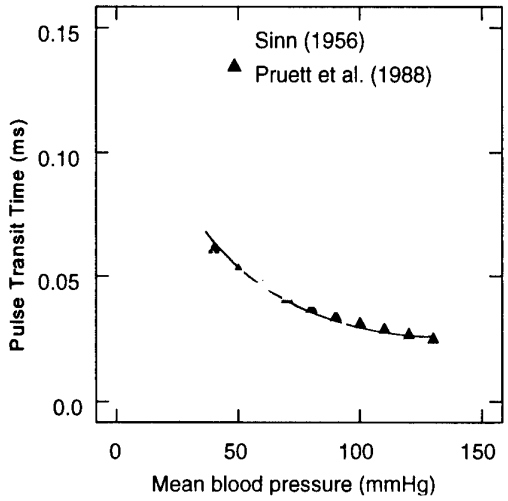

Fig. 15. Relationship between the Pulse Transit Time (ms) and the mean blood pressure according to Sinn (1956) and Pruett et al. (1988).

experimental restrictions. In order to evaluate the relationship between the ear pulse parameters and blood pressure a centrifuge experiment is planned in following phase of this project.

The heart rate during the investigated aerobatic profiles showed no relation with the actual G_z level. This is in disagreement with a previous centrifuge study where a linear relation was found with the G_z level (Krol et al. 1991). It is generally accepted that heart rate increases in order to stabilize the blood pressure during acceleration. However, the heart rate adaptations found during centrifuge experiments where measured during profiles with low onset rates ($<0.3\ G \cdot s^{-1}$) and with only one period of increasing G_z-strain. It is well known that the heart rate needs several seconds to adapt to a new level (Åstrand & Rodahl, 1986). Thus, if the accelerations of the aerobatics profiles are changing within the length of this adaptation period, the heart rate will be lagging in time and a low relation with G_z strain will be found. Furthermore, it is expected that mental effort will affect the heart rate during a profile. However, no information is known about differences in mental load which could explain the low correlation of heart rate with the G_z strain.

The number of subjects which could be analyzed limits for a part the generalization of the results. As indicated the main reason was an inadequate registration of the ECG or G_z signals and not the registration of the ear pulse waveform signal. More pilots will have to be measured during similar G_z-strain profiles to validate the findings of this study. In order to correlate the ear pulse waveform parameters with a blood pressure signal an experiment will be performed in a centrifuge due to experimental restrictions (space and maximal G_z strain) during actual flying. The determination of the correlation between these two signals should provide information about the use of ear pulse waveform parameters as indicators of blood pressures changes.

Conclusions

The amplitude of the ear pulse waveform decreases at higher acceleration during aerobatic profiles. The pulse transit time (PTT) of the ear pulse waveform increases with increasing acceleration during aerobatic profiles. These changes are in agreement with the hypothesis that they reflect a decrease in blood pressure at head level during these profiles.

Heart rate did not show a significant correlation with the acceleration levels during the investigated aerobatic profiles. It is argued that this is the result from the response time of heart rate regulations being not fast enough to follow the speed of changes in the accelerations during the aerobatic profiles.

The results of this study support the use of the amplitude and the PTT of the ear pulse waveform as an online feedback parameter of changes in blood pressure at head level, during exposure of a pilot to accelerations.

It is recommended that in order to correlate the ear pulse waveform parameters with a blood pressure signal an experiment must be performed in a centrifuge. This gives the opportunity to the expand the data to higher G_z strains in combination with the measurement of blood pressure.

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11. AUTHOR(S)
M. Holewijn, M. v/d Endt, J. Rijkelijkhuizen, M. Los

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Netherlands Aeromedical Institute
Kampweg 3, 3769 DE SOESTERBERG, The Netherlands

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15. ABSTRACT (maximum 200 words, 1044 byte)
As a part of a joint study of the National Aeromedical Institute (Soesterberg, the Netherlands), the National Aerospace Laboratory (Amsterdam, the Netherlands) and the Polish Air Force Institute of Aviation Medicine (Warsaw, Poland) an in-flight experiment was performed to evaluate the use of psycho-physiological measures as feedback parameters of physiological and mental strain. The main goal of this study was to evaluate the use of the ear pulse arterial waveform as a potential feedback parameter of a pilot blood pressure status during accelerations. The results of this study showed that the amplitude of the ear pulse waveform decreases with increasing acceleration during aerobatic profiles. The pulse transit time (PTT) of the ear pulse waveform increases with increasing acceleration during aerobatic profiles. These changes agree with the hypothesis that these changes reflect a decrease in blood pressure on head level during these profiles. Heart rates did not show a correlation with the acceleration levels during the investigated aerobatic profiles. It is discussed that this is the result from the response time of heart rate regulations, being not fast enough to follow the changes of the accelerations in the aerobatic profiles. The results of this study support the use of the amplitude and the PTT of the ear pulse waveform as an online feedback parameter of changes in blood pressure at head level, during exposure of a pilot to accelerations.

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